

This Page Is Inserted by IFW Operations  
and is not a part of the Official Record

## **BEST AVAILABLE IMAGES**

Defective images within this document are accurate representations of the original documents submitted by the applicant.

Defects in the images may include (but are not limited to):

- **BLACK BORDERS**
- **TEXT CUT OFF AT TOP, BOTTOM OR SIDES**
- **FADED TEXT**
- **ILLEGIBLE TEXT**
- **SKEWED/SLANTED IMAGES**
- **COLORED PHOTOS**
- **BLACK OR VERY BLACK AND WHITE DARK PHOTOS**
- **GRAY SCALE DOCUMENTS**

**IMAGES ARE BEST AVAILABLE COPY.**

**As rescanning documents *will not* correct images,  
please do not report the images to the  
Image Problems Mailbox.**

This Page Blank (uspto)

This Page Blank (uspto)



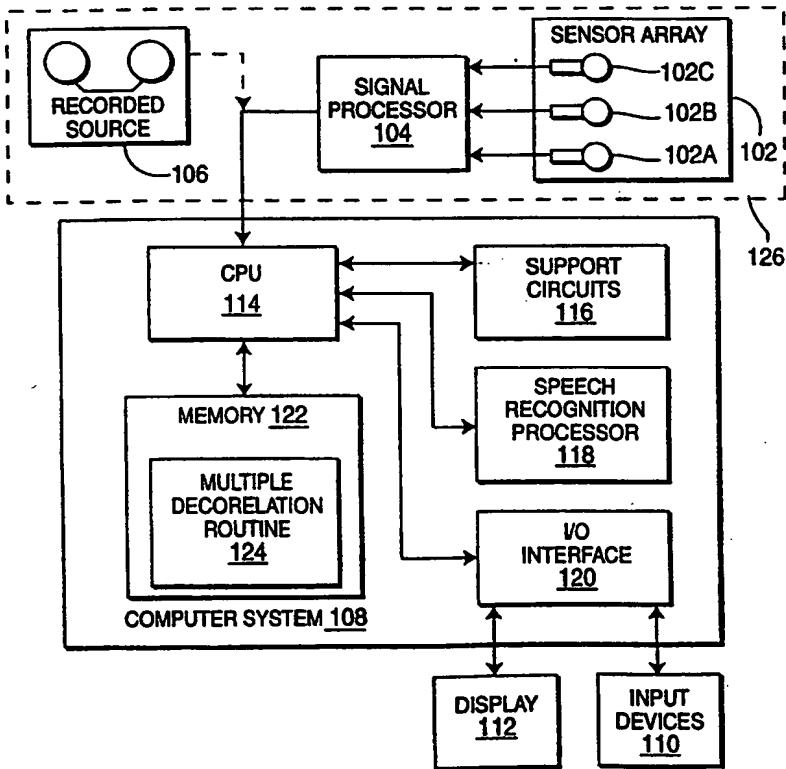
## INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification <sup>6</sup> :  H03H 21/00		A1	(11) International Publication Number: <b>WO 99/52211</b>
			(43) International Publication Date: 14 October 1999 (14.10.99)
<p>(21) International Application Number: <b>PCT/US99/07707</b></p> <p>(22) International Filing Date: 8 April 1999 (08.04.99)</p> <p>(30) Priority Data: 60/081,101 8 April 1998 (08.04.98) US 09/191,217 12 November 1998 (12.11.98) US</p> <p>(71) Applicant: SARNOFF CORPORATION [US/US]; CN 5300, 201 Washington Road, Princeton, NJ 08543-5300 (US).</p> <p>(72) Inventors: PARRA, Lucas; 160 Cabrini Boulevard 131, New York, NY 10033 (US). SPENCE, Clay, Douglas; 136 Cranbury Road, Princeton Junction, NJ 08550 (US).</p> <p>(74) Agents: BURKE, William, J. et al.; CN 5300, Sarnoff Corporation, 201 Washington Road, Princeton, NJ 08543-5300 (US).</p>		<p>(81) Designated States: AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, CA, CH, CN, CU, CZ, DE, DK, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MD, MG, MK, MN, MW, MX, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TR, TT, UA, UG, UZ, VN, YU, ZW, ARIPO patent (GH, GM, KE, LS, MW, SD, SL, SZ, UG, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GW, ML, MR, NE, SN, TD, TG).</p> <p>Published <i>With international search report.</i></p>	

## (54) Title: CONVOLUTIVE BLIND SOURCE SEPARATION USING A MULTIPLE DECORRELATION METHOD

## (57) Abstract

A method and apparatus that performs blind source separation using convolutive signal decorrelation. More specifically, the method accumulates a length of input signal (mixed signal) that comprises a plurality of independent signals from independent signal sources. The invention then divides the length of input signal into a plurality of T-length periods (windows) and performs a discrete Fourier transform (DFT) on the signal within each T-length period. Thereafter, estimated cross-correlation values are computed using a plurality of the average DFT values. A total number of K cross-correlation values are computed, where each of the K values is averaged over N of the T-length periods. Using the cross-correlation values, a gradient descent process computes the coefficients of a FIR filter that will effectively separate the source signals within the input signal. To achieve an accurate solution, the gradient descent process is constrained in that the time-domain values of the filter coefficients can attain only certain values, i.e., the time-domain filter coefficient values  $W(r)$  are constrained within each T-length period to be zero for any time  $t > Q$ . In this manner, a unique solution for the FIR filter coefficients is computed and a filter produced using these coefficients will effectively separate the source signals.



**FOR THE PURPOSES OF INFORMATION ONLY**

Codes used to identify States party to the PCT on the front pages of pamphlets publishing international applications under the PCT.

AL	Albania	ES	Spain	LS	Lesotho	SI	Slovenia
AM	Armenia	FI	Finland	LT	Lithuania	SK	Slovakia
AT	Austria	FR	France	LU	Luxembourg	SN	Senegal
AU	Australia	GA	Gabon	LV	Latvia	SZ	Swaziland
AZ	Azerbaijan	GB	United Kingdom	MC	Monaco	TD	Chad
BA	Bosnia and Herzegovina	GE	Georgia	MD	Republic of Moldova	TG	Togo
BB	Barbados	GH	Ghana	MG	Madagascar	TJ	Tajikistan
BE	Belgium	GN	Guinea	MK	The former Yugoslav Republic of Macedonia	TM	Turkmenistan
BF	Burkina Faso	GR	Greece	ML	Mali	TR	Turkey
BG	Bulgaria	HU	Hungary	MN	Mongolia	TT	Trinidad and Tobago
BJ	Benin	IE	Ireland	MR	Mauritania	UA	Ukraine
BR	Brazil	IL	Israel	MW	Malawi	UG	Uganda
BY	Belarus	IS	Iceland	MX	Mexico	US	United States of America
CA	Canada	IT	Italy	NE	Niger	UZ	Uzbekistan
CF	Central African Republic	JP	Japan	NL	Netherlands	VN	Viet Nam
CG	Congo	KE	Kenya	NO	Norway	YU	Yugoslavia
CH	Switzerland	KG	Kyrgyzstan	NZ	New Zealand	ZW	Zimbabwe
CI	Côte d'Ivoire	KP	Democratic People's Republic of Korea	PL	Poland		
CM	Cameroon	KR	Republic of Korea	PT	Portugal		
CN	China	KZ	Kazakhstan	RO	Romania		
CU	Cuba	LC	Saint Lucia	RU	Russian Federation		
CZ	Czech Republic	LI	Liechtenstein	SD	Sudan		
DE	Germany	LK	Sri Lanka	SE	Sweden		
DK	Denmark	LR	Liberia	SG	Singapore		

## CONVOLUTIVE BLIND SOURCE SEPARATION USING A MULTIPLE DECORRELATION METHOD

This application claims the benefit of U.S. Provisional Application No.

5 60/081,101 filed April 8, 1998, which is herein incorporated by reference.

The invention relates to signal processing and, more particularly, the invention relates to a method and apparatus for performing signal separation using a multiple decorrelation technique.

10

### BACKGROUND OF THE INVENTION

A growing number of researchers have recently published techniques that perform blind source separation (BSS), i.e., separating a composite signal into its constituent component signals without *a priori* knowledge of those signals.

15 These techniques find use in various applications such as speech detection using multiple microphones, crosstalk removal in multichannel communications, multipath channel identification and equalization, direction of arrival (DOA) estimation in sensor arrays, improvement of beam forming microphones for audio and passive sonar, and discovery of independent source signals in various  
20 biological signals, such as EEG, MEG and the like. Many of the BSS techniques require (or assume) a statistical dependence between the component signals to accurately separate the signals. Additional theoretical progress in signal modeling has generated new techniques that address the problem of identifying statistically independent signals - a problem that lies at the heart of source  
25 separation.

The basic source separation problem is simply described by assuming  $d_s$  statistically independent sources  $\mathbf{s}(t) = [s_1(t), \dots, s_{d_s}(t)]^T$  that have been convolved and mixed in a linear medium leading to  $d_x$  sensor signals  $\mathbf{x}(t) = [x_1(t), \dots, x_{d_x}(t)]^T$  that may include additional sensor noise  $\mathbf{n}(t)$ . The convolved, noisy signal is  
30 represented in the time domain by the following equation (known as a forward model):

$$\mathbf{x}(t) = \sum_{\tau=0}^P A(\tau) \mathbf{s}(t-\tau) + \mathbf{n}(t) \quad (1)$$

Source separation techniques are used to identify the  $d_A d_P$  coefficients of the channels  $A$  and to ultimately determine an estimate  $\hat{\mathbf{s}}(t)$  for the unknown source signals.

5        Alternatively, the convolved signal may be filtered using a finite impulse response (FIR) inverse model represented by the following equation (known as the backward model):

$$\mathbf{u}(t) = \sum_{\tau=0}^Q W(\tau) \mathbf{x}(t-\tau) \quad (2)$$

In this representation, a BSS technique must estimate the FIR inverse  
 10      components  $W$  such that the model source signals  $\mathbf{u}(t) = [u_1(t), \dots, u_d(t)]^T$  are statistically independent.

An approach to performing source separation under the statistical independence condition has been discussed in Weinstein et al., "Multi-Channel Signal Separation by Decorrelation", *IEEE Transaction on Speech and Audio Processing*, vol. 1, no. 4, pp. 405-413, 1993, where, for non-stationary signals, a set of second order conditions are specified that uniquely determine the parameters  $A$  in the forward model. However, no specific algorithm for performing source separation based on non-stationarity is given in the Weinstein et al. paper.

20        Early work in the signal processing community had suggested decorrelating the measured signals, i.e., diagonalizing measured correlations for multiple time delays. For an instantaneous mix, also referred to as the constant gain case, it has been shown that for non-white signal decorrelation using multiple filter taps is sufficient to recover the source signals. However, for  
 25      convulsive mixtures of wide-band signals, this technique does not produce a unique solution and, in fact, may generate source estimates that are decorrelated but not statistically independent. As clearly identified by Weinstein et al. in the paper cited above, additional conditions are required to achieve a unique solution of statistically independent sources. In order to find  
 30      statistically independent source signals, it is necessary to capture more than

second order statistics, since statistical independence requires that not only second but all higher cross moments vanish.

In the convolutive case, Yellin and Weinstein in "Multichannel Signal Separation: Methods and Analysis", *IEEE Transaction on Signal Processing*; vol. 5 44, no. 1, pp. 106-118, January 1996 established conditions on higher order multi-tap cross moments that allow convolutive cross talk removal. Although the optimization criteria extends naturally to higher dimensions, previous research has concentrated on a two dimensional case because a multi-channel FIR model (see equation 2) can be inverted with a properly chosen architecture 10 using estimated forward filters. Heretofore, for higher dimensions, finding a stable approximation of the forward model has been illusive.

These prior art techniques generally operate satisfactorily in computer simulations but perform poorly for real signals, e.g., audio signals. One could speculate that the signal densities of the real signals may not have the 15 hypothesized structures, the higher order statistics may lead to estimation instabilities, or a violation of the signal stationarity condition may cause inaccurate solutions.

Therefore, there is a need in the art for a blind source separation technique that accurately performs convolutive signal decorrelation.

20

#### SUMMARY OF THE INVENTION

The disadvantages of the prior art are overcome by a method and apparatus that performs blind source separation using convolutive signal decorrelation by simultaneously diagonalizing second order statistics at multiple 25 time periods. More specifically, the invention accumulates a length (segment) of input signal that comprises a mixture of independent signal sources. The invention then divides the length of input signal into a plurality of T-length periods (windows) and performs a discrete Fourier transform (DFT) on the mixed signal over each T-length period. Thereafter, the invention computes K 30 cross-correlation power spectra that are each averaged over N of the T-length periods. Using the cross-correlation power values, a gradient descent process computes the coefficients of a FIR filter that will effectively separate the source

signals within the input signal by simultaneously decorrelating the K cross-correlation power spectra. To achieve an accurate solution, the gradient descent process is constrained in that the time-domain values of the filter coefficients can attain only certain values, i.e., the time-domain filter coefficient values  $W(\tau)$

5 are constrained within the T-length period to be zero for any time  $\tau > Q < T$ . In this manner, the so-called "permutation problem" is solved and a unique solution for the FIR filter coefficients is computed such that a filter produced using these coefficients will effectively separate the source signals.

Generally, the invention is implemented as a software routine that is

10 stored in a storage medium and executed on a general purpose computer system. However, a hardware implementation is readily apparent from the following detailed description.

The present invention finds application in a voice recognition system as a signal preprocessor system for decorrelating signals from different sources such

15 that a voice recognition processor can utilize the various voice signals that are separated by the invention. In response to the voice signals, the voice recognition processor can then produce computer commands or computer text.

20 BRIEF DESCRIPTION OF THE DRAWINGS

The teachings of the present invention can be readily understood by considering the following detailed description in conjunction with the accompanying drawings, in which:

FIG. 1 depicts a system for executing a software implementation of the

25 present invention;

FIG. 2 is a flow diagram of a method of the present invention;

FIG. 3 depicts a frequency domain graph of the filter coefficients generated by the present invention; and

FIG. 4 depicts a time domain graph of the filter coefficients generated by

30 the present invention.

To facilitate understanding, identical reference numerals have been used, where possible, to designate identical elements that are common to the figures.

### DETAILED DESCRIPTION

5

The present invention estimates values of parameters  $W$  for the backward model of equation 2 by assuming non-stationary source signals and using a least squares (LS) optimization to estimate  $W$  as well as signal and noise powers. The invention transforms the source separation problem into the frequency domain 10 and solves simultaneously a source separation problem for every frequency.

FIG. 1 depicts a system 100 for implementing the source separation method of the present invention. The system 100 comprises a convolved signal source 126 that supplies the signal that is to be separated into its component signals and a computer system 108 that executes the multiple decorrelation 15 routine 124 of the present invention. The source 126 may contain any source of convolved signals, but is illustratively shown to contain a sensor array 102, a signal processor 104 and a recorded signal source 106. The sensor array contains one or more transducers 102A, 102B, 102C such as microphones. The transducers are coupled to a signal processor 104 that performs signal 20 digitization. A digital signal is coupled to the computer system 108 for signal separation and further processing. A recorded signal source 106 may optionally form a source of the convolutive signals that require separation.

The computer system 108 comprises a central processing unit (CPU) 114, a memory 122, support circuits 116, and an input/output (I/O) interface 120. 25 The computer system 108 is generally coupled through the I/O interface 120 to a display 112 and various input devices 110 such as a mouse and keyboard. The support circuits generally contain well-known circuits such as cache, power supplies, clock circuits, a communications bus, and the like. The memory 122 may include random access memory (RAM), read only memory (ROM), disk 30 drive, tape drive, and the like, or some combination of memory devices. The invention is implemented as the multiple decorrelation routine 124 that is stored in memory 122 and executed by the CPU 114 to process the signal from

the signal source 126. As such, the computer system 108 is a general purpose computer system that becomes a specific purpose computer system when executing the routine 124 of the present invention. Although a general purpose computer system is illustratively shown as a platform for implementing the 5 invention, those skilled in the art will realize that the invention can also be implemented in hardware as an application specific integrated circuit (ASIC), a digital signal processing (DSP) integrated circuit, or other hardware device or devices. As such, the invention may be implemented in software, hardware, or a combination of software and hardware.

10 The illustrative computer system 108 further contains speech recognition processor 118, e.g., a speech recognition circuit card or a speech recognition software, that is used to process the component signals that the invention extracts from the convolutive signal. As such, a conference room having a plurality of people speaking and background noise can be monitored with 15 multiple microphones 102. The microphones 102 produce a composite speech signal that requires separation into component signals if a speech recognition system is to be used to convert each person's speech into computer text or into computer commands. The composite speech signal is filtered, amplified and digitized by the signal processor 104 and coupled to the computer system 108.

20 The CPU 114, executing the multiple decorrelation routine 124, separates the composite signal into its constituent signal components. From these constituent components, background noise can easily be removed. The constituent components without noise are then coupled to the speech recognition processor 118 to process the component signals into computer text or computer 25 commands. In this manner, the computer system 108 while executing the multiple decorrelation routine 124 is performing signal pre-processing or conditioning for the speech recognition processor 118.

FIG. 2 depicts a flow diagram of the multiple decorrelation routine 124 of the present invention. At step 200, the convolutive (mixed) signal is input, the 30 signal is parsed into a plurality of windows containing T-samples of the input signal  $X(t)$ , and the routine produces a discrete Fourier transform (DFT) values for each window  $\chi(t)$ , i.e., one DFT value for each window of length T samples.

At step 202, the routine 124 uses the DFT values to accumulate K cross-correlation power spectra, where each of the K spectra are averaged over N windows of length T samples.

For non-stationary signals, the cross correlation estimates will be 5 dependent on the absolute time and will indeed vary from one estimation segment (an NT period) to the next. The cross correlation estimates computed in step 204 are represented as:

$$\hat{R}_x(t, v) = \frac{1}{N} \sum_{n=0}^{N-1} \chi(t + nT, v) \chi^T(t + nT, v) \quad (5)$$

where:

10  $\chi(t + nT, v) = FFT \ X(t + nT)$   
 $X(t) = [x(t) - x(t + T - 1)]$

and  $\chi(v)$  is the FFT of the input signal within a window containing T samples.

As such, the routine, at step 204, computes a matrix for each time t and for each frequency v and then sums all the matrix components with each other matrix 15 component. Steps 206, 208, 210 and 212 iterate the correlation estimation of step 204 over n=0 to N and k=0 to K to produce the K spectra.

Equation 5 can then be simplified to a matrix representation:

$$\hat{R}_x(t, v) = A(v) \Lambda_s(t, v) A^H(v) + \Lambda_n(t, v) \quad (6)$$

If N is sufficiently large,  $\Lambda_s(t, v)$  and  $\Lambda_n(t, v)$  can be modeled as diagonal 20 matrices due to the signal independence assumption. For Equation 6 to be linearly independent for different times, it will be necessary that  $\Lambda_s(t, v)$  changes over time, i.e., the signals are non-stationary.

Using the cross correlation estimates of equation 6, the invention computes the source signals using cross-power-spectra satisfying the following 25 equation:

$$\Lambda_s(t, v) = W(v)(\hat{R}_x(t, v) - \Lambda_n(t, v))W^H(v) \quad (7)$$

In order to obtain independent conditions for every time period, the time periods are generally chosen to have non-overlapping estimation times for  $\hat{R}_x(t_k, v)$ , i.e.,  $t_k = kTN$ . But if the signals vary sufficiently fast, overlapping

estimation times may be utilized. Furthermore, although the windows T are generally sequential, the windows may overlap one another such that each DFT value is derived from signal information that is also contained in the previous window. In an audio signal processing system, the specific value of T is selected 5 based upon room acoustics of the room in which the signals are recorded. For example, a large room with many reverberation paths requires a long window T such that the invention can process a substantial amount of signal information to achieve source signal separation. The value of N is generally determined by the amount of available data for processing. Typical values are N = 20, T = 10 1024 samples and K = 5.

The inventive method computes a multipath channel W (i.e., the tap values of a multidimensional FIR filter) that simultaneously satisfies equation 7 for K estimation periods, e.g., 2 to 5 estimation periods for processing audio signals. Such a process is performed at steps 214, 216, 218 (collectively a filter 15 parameter estimation process 224) and is represented using a least squares estimation procedure as follows:

$$\hat{W}, \hat{\Lambda}_s, \hat{\Lambda}_n = \arg \min_{\substack{W, \Lambda_s, \Lambda_n \\ W(t) \geq 0, t > Q \\ W_{ii}(v) = 1}} \sum_{v=1}^V \sum_{k=1}^K \|E(k, v)\|^2$$

where (8)

$$E(k, v) = W(v)(\hat{R}_s(k, v) - \Lambda_n(k, v))W^H(v) - \Lambda_s(k, v)$$

For simplicity, a short form nomenclature has been used in equation 8, where  $\Lambda_s(k, v) = \Lambda_s(t_k, v)$  and  $\Lambda_n = \Lambda_n(t_1, v) \oplus \Lambda_n(t_2, v) \oplus \dots \oplus \Lambda_n(t_K, v)$  and the same simplified notation 20 also applies to  $\Lambda_n(t, v)$  and  $R_s(t, v)$ .

To produce the parameters W, a gradient descent process 224 (containing steps 214, 216, 218, and 220) is used that iterates the values of W as cost function (8) is minimized. In step 216, the W values are updated as  $W^{new} = W^{old} - \mu \nabla_w E$ , where  $\nabla_w E$  is the gradient step value and  $\mu$  is a weighting constant that 25 controls the size of the update.

More specifically, the gradient descent process determines the gradient values as follows.

$$\frac{\partial E}{\partial W^*(v)} = \sum_{k=1}^K E(k, v) W(v) B^H(k, v) \quad (10)$$

$$\frac{\partial E}{\partial \hat{\Lambda}_s^*(k)} = -\text{diag}(E(k, v)) \quad (11)$$

$$\frac{\partial E}{\partial \hat{\Lambda}_n^*(k)} = -\text{diag}(W^H(v) E(k, v) W(v)) \quad (12)$$

$$B(k, v) \equiv \hat{R}_x(k, v) - \Lambda_n(k, v) \quad (13)$$

5 With equation 11 equal to zero, the routine can solve explicitly for parameters  $\Lambda_s(k, v)$ , while parameters  $\Lambda_n(k, v)$  and  $W(v)$  are computed with a gradient descent rule, e.g., new values of  $\Lambda_s(k, v)$  and  $W(v)$  are computed with each pass through the routine until the new values of  $W(v)$  are not very different from the old values of  $W(v)$ , i.e.,  $W$  is converged.

10 Note that equation 8 contains an additional constraint on the filter size in the time domain. Up to that constraint it would seem the various frequencies  $v = 1, \dots, T$  represent independent problems. The solutions  $W(v)$  however are restricted to those filters that have no time response beyond  $\tau > Q \ll T$ . Effectively, the routine parameterizes  $Td, d_x$  filter coefficients in  $W(v)$  with  $Qd, d_x$  parameters  $W(\tau)$ . In practice, the values of  $W$  are produced in the frequency domain, at step 214, e.g.,  $W(v)$ , then, at step 218, an FFT is performed on these frequency domain values to convert the values of  $W(v)$  to the time domain, e.g.,  $W(\tau)$ . In the time domain, any  $W$  value that appears at a time greater than a time  $Q$  is set to zero and all values in the range below  $Q$  are not adjusted. The 15 adjusted time domain values are then converted using an inverse FFT back to the frequency domain. By zeroing the filter response in the time domain for all time greater than  $Q$ , the frequency response of the filter is smoothed such that a unique solution at each frequency is readily determined.

20 FIG. 3 depicts an illustration of two frequency responses 302A and 302B and FIG. 4 depicts an illustration of their corresponding time-domain responses 304A and 304B. The least squares solutions for the coefficients are found using a gradient descent process performed at step 224 such that an iterative 25 approach is used to determine the correct values of  $W$ . Once the gradient in

equation 10 becomes "flat" as identified in step 220, the routine, at step 222, applies the computed filter coefficients to an FIR filter. The FIR filter is used to filter the samples of the input (mixed) signal  $x(t)$  in the time period KNT in length. The FIR filter generates, at step 226, the decorrelated component 5 signals of the mixed signal. Then, the routine at step 228 gets the next KNT number of samples for processing and proceeds to step 200 to filter the next KNT samples. The previous KNT samples are removed from memory.

As mentioned above, the gradient equations are constrained to remain in the subspace of permissible solutions with  $W(\tau) = 0$  for  $\tau > Q \ll T$ . This is 10 important since it is a necessary condition for equation 8 to achieve a good approximation.

In practical applications, such as voice recognition signal preprocessing, the inventive routine substantially enhances the performance of the voice recognition accuracy, i.e., word error rates improve by 5 to 50% and in some 15 instances approach the error rate that is achieved when no noise is present. Error rate improvement has been shown when a desired voice signal is combined with either music or another voice signal as background noise.

Although various embodiments which incorporate the teachings of the present invention have been shown and described in detail herein, those skilled 20 in the art can readily devise many other varied embodiments that still incorporate these teachings.

What is claimed is:

1. A method for separating a mixed signal into a plurality of component signals comprising the steps of:

5        (a) producing a plurality of discrete Fourier transform (DFT) values, where a DFT value is produced for every T samples of said mixed signal;

      (b) producing a cross correlation estimation matrix that is averaged over N of the DFT values;

      (c) repeating step (b) K times to produce a plurality of cross correlation 10 estimation values;

      (d) computing, using a gradient descent process, a plurality of filter coefficients for a finite impulse response (FIR) filter using the cross correlation estimation values; and

      (e) filtering the mixed signal using the FIR filter having the computed 15 filter coefficients to separate the mixed signal into the plurality of component signals.

2. The method of claim 1 wherein step (d) further comprising the steps of:

      (d1) transforming the filter coefficients from the frequency domain into 20 the time domain;

      (d2) zeroing any filter coefficients having a value other than zero for any time that is greater than a predefined time Q to produce adjusted time domain filter coefficients, where Q is less than T; and

      (d3) transforming the adjusted time domain filter coefficients from the 25 time domain into the frequency domain to produce the filter coefficients used in the gradient descent process.

3. The method of claim 1 wherein the cross correlation estimation values are produced in step (b) using the following equation:

$$30 \quad \hat{R}_x(t, v) = \frac{1}{N} \sum_{n=0}^{N-1} \chi(t + nT, v) \chi^T(t + nT, v)$$

where  $\chi(t, v)$  is the mixed signal in the frequency domain.

4. The method of claim 3 wherein the gradient descent process minimizes the function:

$$\sum_{v=1}^T \sum_{k=1}^K \|E(k, v)\|^2$$

where  $E(k, v)$  is an error function.

5 5. Apparatus for separating a mixed signal into a plurality of component signals comprising:

means for producing a plurality of discrete Fourier transform (DFT) values, where a DFT value is produced for every T samples of said mixed signal;

means for producing a plurality of cross correlation estimation values

10 using the DFT values;

a gradient descent processor for computing a plurality of filter coefficients for a finite impulse response (FIR) filter using the cross correlation estimation values; and

a filter for filtering the mixed signal using the FIR filter having the

15 computed filter coefficients to separate the mixed signal into the plurality of component signals.

6. The apparatus of claim 5 wherein the gradient descent processor further comprises:

20 a first transformer for transforming the filter coefficients from the frequency domain into the time domain;

means for zeroing any filter coefficients having a value other than zero for any time that is greater than a predefined time Q to produce adjusted time domain filter coefficients, where Q is less than T; and

25 a second transformer for transforming the adjusted time domain filter coefficients from the time domain into the frequency domain to produce the filter coefficients used in the gradient descent process.

7. The apparatus of claim 5 wherein the cross correlation estimation values are 30 produced using the following equation:

$$\hat{R}_x(t, v) = \frac{1}{N} \sum_{n=0}^{N-1} \chi(t + nT, v) \chi^T(t + nT, v)$$

where  $\chi(t, v)$  is the mixed signal in the frequency domain.

8. The apparatus of claim 5 further comprising a voice recognition system for  
5 processing at least one of the plurality of component signals.

9. The apparatus of claim 5 further comprising a plurality of microphones that  
produce the mixed signal.

10 10. The apparatus of claim 5 wherein the gradient descent processor minimizes  
the function:

$$\sum_{v=1}^T \sum_{k=1}^K \|E(k, v)\|^2$$

where  $E(k, v)$  is an error function.

11. A computer readable storage medium containing a program that, when  
15 executed upon a general purpose computer system causes the general purpose  
computer system to become a specific purpose computer system that performs a  
method for separating a mixed signal into a plurality of component signals  
comprising the steps of:

(a) producing a plurality of discrete Fourier transform (DFT) values,  
20 where a DFT value is produced for every T samples of said mixed signal;

(b) producing a cross correlation estimation matrix that is averaged over  
N of the DFT values;

(c) repeating step (b) K times to produce a plurality of cross correlation  
estimation values;

25 (d) computing, using a gradient descent process, a plurality of filter  
coefficients for a finite impulse response (FIR) filter using the cross correlation  
estimation values; and

(e) filtering the mixed signal using the FIR filter having the computed filter coefficients to separate the mixed signal into the plurality of component signals.

5 12. The computer readable medium of claim 11 wherein step (d) of the method further comprises the steps of:

(d1) transforming the filter coefficients from the frequency domain into the time domain;

10 (d2) zeroing any filter coefficients having a value other than zero for any time that is greater than a predefined time Q to produce adjusted time domain filter coefficients, where Q is less than T; and

(d3) transforming the adjusted time domain filter coefficients from the time domain into the frequency domain to produce the filter coefficients used in the gradient descent process.

15

13. The computer readable medium of claim 11 wherein the cross correlation estimation values are produced in step (b) using the following equation:

$$\hat{R}_x(t, v) = \frac{1}{N} \sum_{n=0}^{N-1} \chi(t + nT, v) \chi^T(t + nT, v)$$

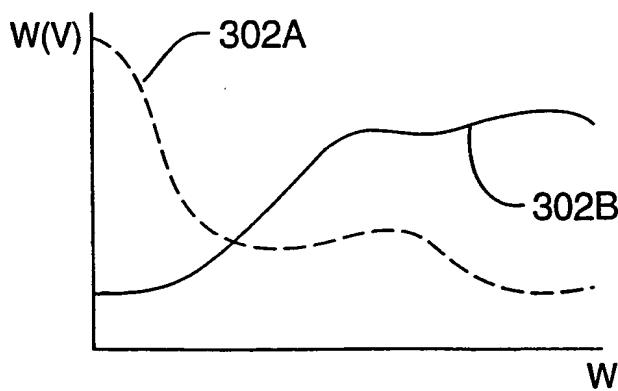
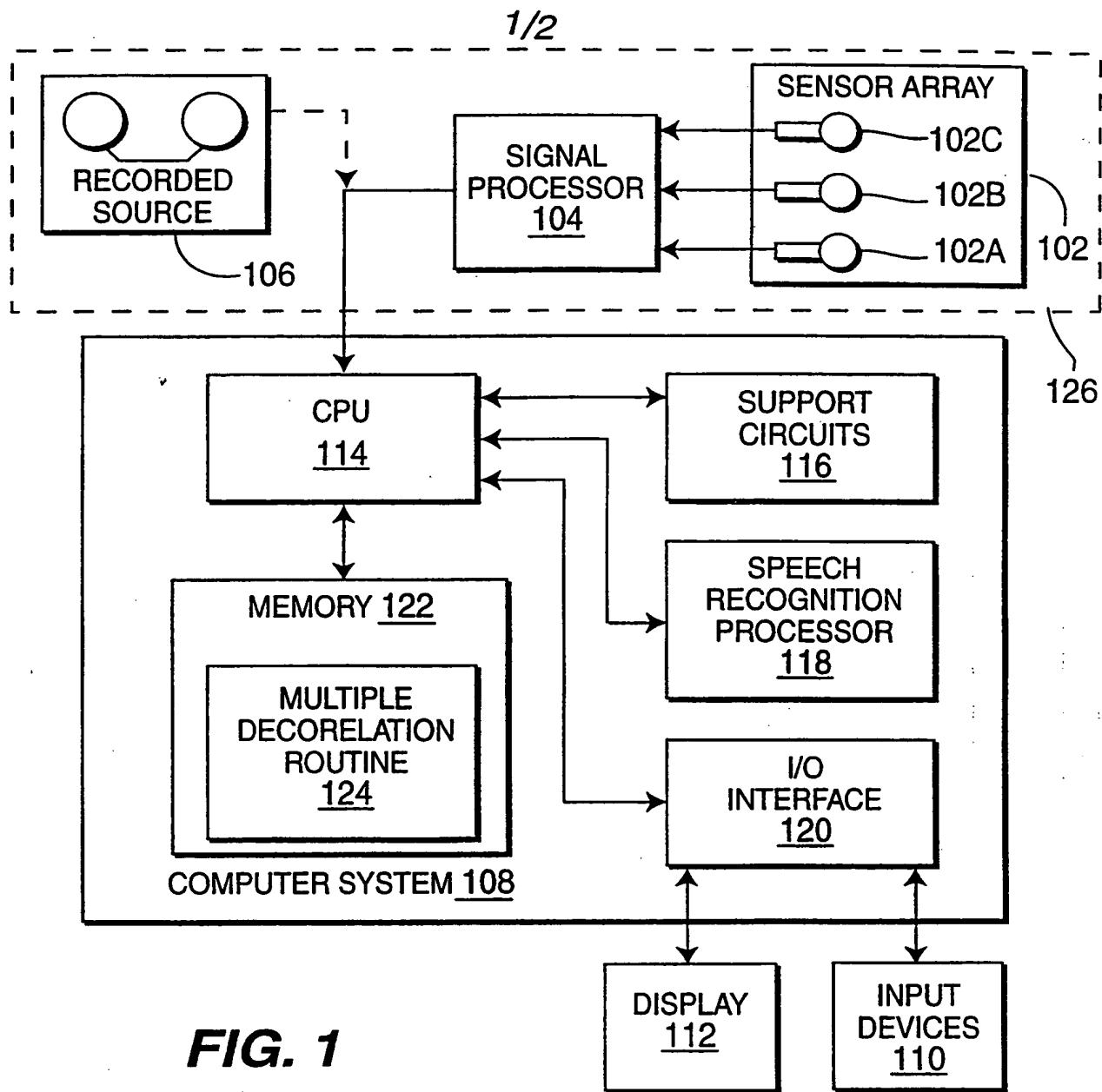
where  $\chi(t, v)$  is the mixed signal in the frequency domain

20

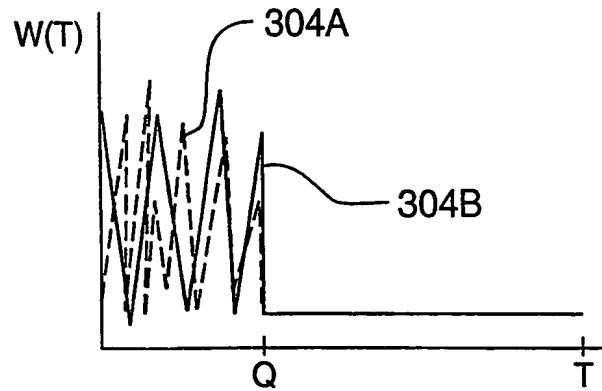
14. The computer readable medium of claim 11 wherein the gradient descent process minimizes the function:

$$\sum_{v=1}^T \sum_{k=1}^K \|E(k, v)\|^2$$

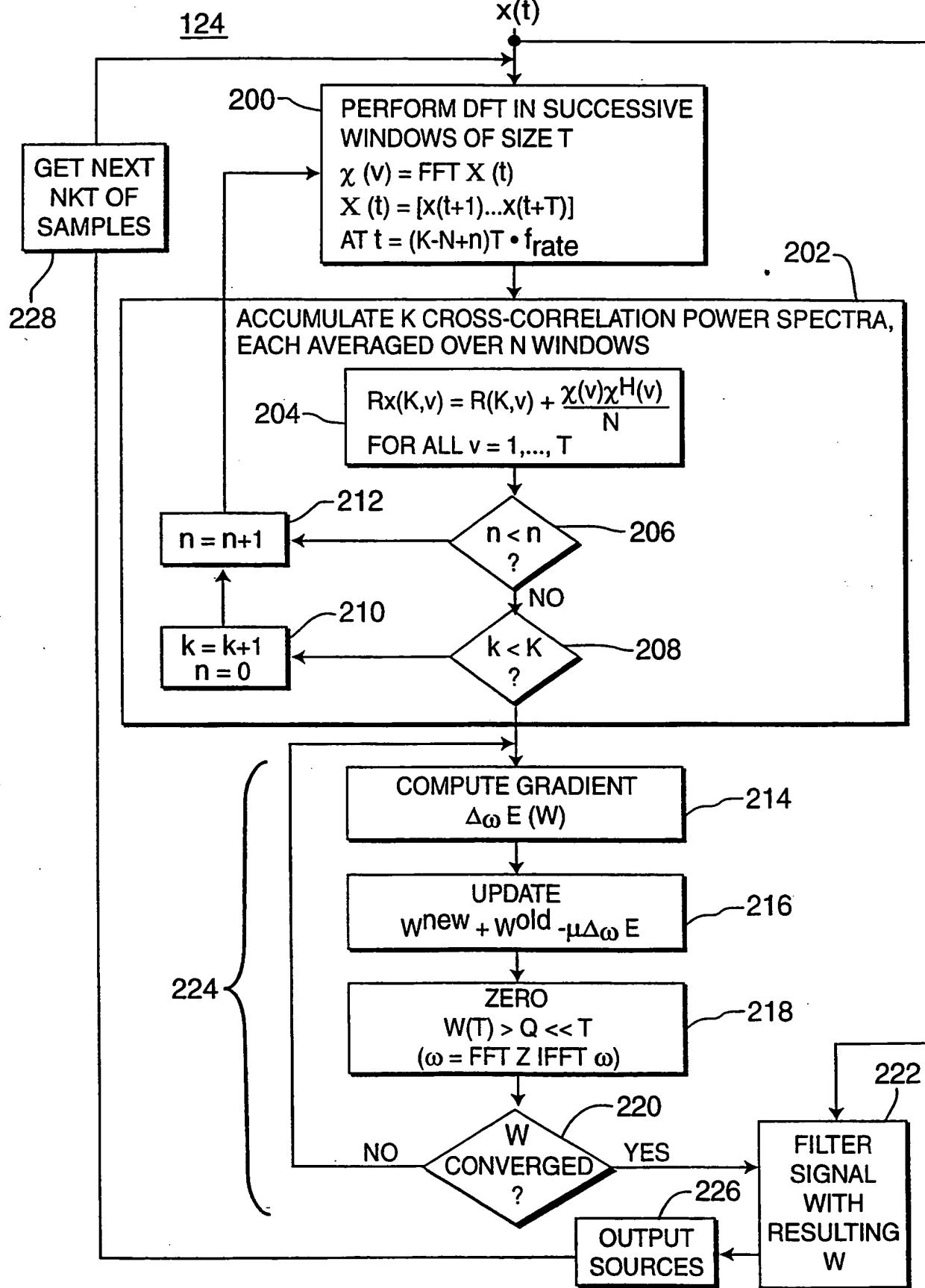
where  $E(k, v)$  is an error function.



**FIG. 3**



**FIG. 4**

**FIG. 2**

# INTERNATIONAL SEARCH REPORT

International Application No

PCT/US 99/07707

**A. CLASSIFICATION OF SUBJECT MATTER**

IPC 6 H03H21/00

According to International Patent Classification (IPC) or to both national classification and IPC

**B. FIELDS SEARCHED**

Minimum documentation searched (classification system followed by classification symbols)

IPC 6 H03H

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	EP 0 565 479 A (UNIV RAMOT) 13 October 1993 (1993-10-13) the whole document	1

Further documents are listed in the continuation of box C.

Patent family members are listed in annex.

\* Special categories of cited documents :

- \*A\* document defining the general state of the art which is not considered to be of particular relevance
- \*E\* earlier document but published on or after the international filing date
- \*L\* document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
- \*O\* document referring to an oral disclosure, use, exhibition or other means
- \*P\* document published prior to the international filing date but later than the priority date claimed

\*T\* later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

\*X\* document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

\*Y\* document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

\*&\* document member of the same patent family

Date of the actual completion of the international search

13 July 1999

Date of mailing of the international search report

19/07/1999

Name and mailing address of the ISA

European Patent Office, P.B. 5818 Patentlaan 2  
NL - 2280 HV Rijswijk  
Tel. (+31-70) 340-2040, Tx. 31 651 epo nl,  
Fax: (+31-70) 340-3016

Authorized officer

Coppieters, C

# INTERNATIONAL SEARCH REPORT

## Information on patent family members

International Application No

PCT/US 99/07707

Patent document cited in search report	Publication date	Patent family member(s)		Publication date
EP 0565479	A 13-10-1993	IL 101556	A 04-08-1996	JP 6021838 A 28-01-1994
		US 5539832	A 23-07-1996	